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Measurement of Wind Sensor Characteristics

G R Pearce

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Measurement of Wind Sensor Characteristics

G R Pearce

Summary

The dynamic response characteristics of anemometer systems (Met. Office Mark 4 and Mark 5, and Porton) and vane systems (Met. Office Mark 4 and Mark 5) are measured and compared.

The responses of their associated pen-recorders (Met. Office Mark 4 and Mark 5) are investigated.

The theory of Wieranga (1967) describing the inter-relationship of vane response parameters is found to work for the Met. Office vane.

Introduction

To investigate how accurately an anemograph trace records real fluctuations in wind speed and direction, the responses of each part of the speed and direction sensing systems need to be known. Each system essentially comprises a sensor and pen-recorder. The pen-recorder is a first order system. So too is the cup anemometer if its initial motion and dependence on wind speed are ignored. The vane is a second order system. The combination of pen-recorder and sensors results in a third order system, but by investigating their responses separately the use of tensor calculus is precluded.

A first order system obeys the equation of motion:

$$\dot{y} + \frac{1}{\tau} y = f(t) \qquad (1)$$

y is the dependant variable, anemometer speed or pen displacement

τ is a constant known as the time constant.

Its reaction to a step change, A, in y is:

$$y = A\left(1 - \exp\left[-t/\tau\right]\right)$$

Thus when $t = \tau$ then $y/A = (1 - 1/e) = 0.63$.

A pure first-order system, such as the pen recorder, completes 63% of its reaction to a step, A, applied at time, t = 0, after the time constant τ, has elapsed (See Fig 1).

The anemometer's response is more complicated because its time constant decreases with increasing wind speed, i.e. it reacts faster at high wind speed. When applied to an anemometer, equation (1) contains a speed dependent variable:

$$y' + \frac{1}{u\tau} y = f(u, t) \quad (2)$$ (where u is wind speed)

Distance constant is a more meaningful parameter for describing anemometer response. The length of air that must pass the anemometer for it to complete 63% of its reaction gives a direct indication of response. This length remains generally constant over the operational range of any anemometer whose motion is described by equation (2). Thus the distance constant is defined as the product of wind speed and time constant.

The vane's response to a step change in wind direction is described mathematically by

$$y'' + 2h\omega_n y' + \omega_n^2 = f(t) \quad (3)$$ (Macready et al [1964])

where y is the dependent variable - output voltage and h and w_n are constants known as the damping ratio and natural (angular) frequency respectively.

This response can be expressed using three parameters, damping ratio, decay distance and natural wavelength.

Damping ratio, h, indicates the degree of overshoot of the vane. When h = 0 the vane will exhibit SHM. When h = 1 the vane just fails to overshoot (critical damping). All vanes are underdamped and thus have a damping ratio 0 h 1.

Decay distance, u.t, indicates the speed of response. The term is analagous to the distance constant in that it is the length of air that must pass for the

sensor to complete 63% of its reaction, but in this case it is applied to the envelope containing the oscillation.

Damped wavelength, λ_d, is the length of air that passes whilst the vane completes one oscillation. This wavelength increases as the magnitude of the overshoot peaks described by the vane decrease. Thus as damping ratio, h, approaches 1 the damped wavelength tends to infinity.

The limiting value of damped wavelength is the only fixed value describing the rate of oscillation of the vane. This is called the natural wavelength and is related to the natural frequency, w_n, of the vane by

$$\lambda_n = 2\pi u / \omega_n$$ where u is wind speed

The natural wavelength of a "perfect" vane is constant whatever the degree of overshoot is. This is because the limiting value h = 0 is considered, and this corresponds to the SHM executed by the vane at its natural frequency. It can only be found, therefore, if the damped wavelength and damping ratio are known. The equation used is:

$$\lambda_n = \lambda_d \left(1 - h^2\right)^{1/2}$$

General description of the wind sensors investigated

Anemometers

The Met Office Mark 4 comprises 3 cups which turn a 6 pole ac generator. The current generated passes through a full-wave rectifier before powering a galvanometric dial or a pen recorder. The number of dials and/or recorders is fixed and any absent ones are replaced by accurate dummies to maintain a constant load on the generator.

The Met Office Mark 5 uses the same head but modified with a larger pole gap in the generator. A transducer converts each a.c. cycle to a single digital pulse. These pulses are summed to give a d.c. voltage indicative of wind speed.

The Porton is much smaller and lighter anemometer. It has 3 polycarbonate conical cups, and the transducer is located in the head.

The Mark 4 indicates wind speed by the size of the rms generated voltage, whereas the Mark 5 and Porton use the frequency of this voltage to trigger an indicative dc voltage.

Vanes

The magslip system, as used in the Mark 4 vane, comprises a coil directly attached to the fin. The coil is set in the centre of a triangle of coils through which a small current flows. As the fin moves, a current is induced in the attached coil. This current flows round another coil set in the middle of a similar triangle of coils. This coil, with a dial attached moves as the fin does. There is no steady output voltage from the magslip and it is therefore impossible to analyze the vane free from its system. For this investigation the magslip of the Mark 4 vane used was replaced by a potentiometer.

The Mark 5 system uses a Mark 4 vane. The changes in voltage from the magslip, trigger an indicative dc voltage in the transducer. (NB This transducer is separate to the anemometer one which is included in the same unit). 0-10 volts dc represent the 0° - 540° direction range with automatic resetting if the direction appears to go out of the range, eg. the vane rotates twice.

Experimental details

Anemometers

The method of Schubauer et al (1954) was used to apply step gusts of different speeds to the anemometers under test. An anemometer was clamped in the Met Office tunnel and suddenly released. Using systems as shown in figs 3a and 3b for the Mark 4 and Mark 5 respectively, a trace similar to fig 1 was obtained from the UV oscillograph. (The Porton had a similar system to the Mark 5). Optimum smoothing was achieved by adjusting the filter to give minimum ripple in the trace without significantly effecting the response curve. $11H_z$ normal, cut-off frequency gave best results.

The time constant for a given anemometer and given step was found by plotting the values of $\log\left(\frac{A-v}{A}\right)$ against t at 0.1s intervals. The time constant was obtained

by finding the time between the intercepts of the best straight line with the abscissas log (A-y)/A = 1.000 and log (A-y)/A = 0.37. These abscissas corresponded to zero and 63% reaction respectively. This method overcame 2 problems: the non-conformity of the anemometer's initial motion, and the displacement of the start of this motion from a timing line. The Time constant measurement method was found to be more accurate at high wind speed than low. The standard error was found to be $\pm$ 0.01s at 60 knots and $\pm$ 0.02s at 30 knots.

The time constants for the responses of the three anemometers are summarised in Table 1. Also included are those when the Mark 4 and Mark 5 heads were interchanged. These curves are compared in fig 6.

The distance constants of the Mark 4 and Mark 5 were found by plotting reciprocal time constant against wind speed (fig 7). Reciprocation of the "least squares" gradient gave a distance constant of 6.3m for the Mark 4 over the range 0.80 knots, and 7.5m for the Mark 5 for 0.60 knots.

Instantaneous distance constant was also plotted (fig 8). This was found by multiplying the time constant by the respective speed.

The threshold (initial starting speed) of the Mark 4 was found to be 6.4 knots whereas that of the Mark 5 was 3.5 knots. These were found by slowly increasing the tunnel speed from zero. The anemometer arms were placed in 120° different positions in repeat runs so that a fair value was obtained. The manufacturers claim a threshold of 0.5 knots for the Porton.

The 95% response times, corresponding to $t = 3\tau$ and thus $y/A = 1 - 1/e^3$, were found from experimental data in the same way as the time constants. These are included in table 1 with values calculated from the time constants, found by multiplying the time constants by three.

The Porton output voltage calibration with windspeed is shown in fig 15.

Vanes

Wieranga (1964), Mazarella (1972) and others say that wind vanes do not behave as second order systems for step changes in direction greater than 15°-20°. For

this reason, angles of 9.5°, 12.3° and 15.5° were specifically investigated. The step change in direction was applied in exactly the same way as for the anemometer. The vane was clamped at a particular angle and suddenly released. Using a system as shown in fig 3c a trace similar to fig 2 was obtained from the UV oscillograph. A subtracting voltage was necessary to remove the voltage indicating the vanes position in its 0-540° range leaving a small varying voltage, due to the step change in direction, which gave a full scale deflection on the UV oscillograph.

A small lapse time of 0.1s after release was observed in the Mark 5 before the recorder began to react. This was probably due to triggering times in the transducer.

Table 2 and figs 9 to 12 show the variation of damping ration, decay distance, damped wavelength and natural wavelength with wind speed for the Mark 4 vane and the Mark 5 vane system at the investigated step direction changes.

Damping ratio was found by dividing the first peak A, by the initial condition A_o. This value, $\frac{A1}{Ao}$ gave the appropriate value of h when a log. decrement method on the curve $h = (\log_{10} A_o/A_n)\,(1.862 + [\log_{10} A_o/A_n])^{-\frac{1}{2}}$ was used (Gill)

Decay distance was found by multiplying the 63% response time of the envelope, by the wind speed.

Damped wavelength was found by multiplying the time, $td = 2t$, for one oscillation of the vane by wind speed, i.e.

$$\lambda_d = u.t_d = 2u.t_1$$

Natural wavelength was calculated from damped wavelength using the value of h already calculated.

$$\lambda_n = u.t_n = \lambda_d (1 - h^2)^{\frac{1}{2}}$$

Recorders

The time constants of the Mark 4, Mark 5 and UV oscillograph recorders were found using a method described by Atkinson. A log-log plot of their frequency responses to an accurate sinusoidal input were drawn (fig 13). This plot is called a Bode

diagram. The tangent to the Bode diagram curve at the point where its gradient was 20dB/decade was produced to the OdB abscissa. The recorders "cut-off" frequency was found from the value of angular frequency at the intersection. The recorder's time constant was found by reciprocating this frequency.

Results

Table 1 Anemometer systems' time constants (s)

		Wind velocity/knots								
		5	10	20	30	40	50	60	70	80
Time in Constants (in) (seconds)	Mark 4 system,		1.39	0.68	0.45	0.32	0.25	0.20	0.17	0.16
	Mark 5 system		1.40	0.66	0.52	0.36	0.28	0.24	0.22	0.21
	Mark 4 head in Mark 5 system				0.45	0.36	0.32	0.25		
	Mark 5 head in Mark 4 system				0.38	0.30	0.27	0.21		
	Porton	0.83	0.46	0.20	0.17	0.15	0.13	0.12	0.14	0.11
95% Time constants (in) (seconds)	Mark 4-experimentally determined		4.01	2.12	1.31	0.95	0.76	0.61	0.55	0.50
	Mark 4-Time Constant X 3		4.17	2.04	1.35	0.96	0.75	0.60	0.51	0.48
	Mark 5-experimentally determined		4.22	2.05	1.58	1.09	0.85	0.72	0.67	0.64
	Mark 5-Time constant X 3		4.20	1.98	1.56	1.08	0.84	0.72	0.66	0.63

Table 2 Wind Vane

Response parameters

	vane type	angle of attack	Wind velocity/knots 5	10	20	30	40	50	60	70
Damping Ratio	Mark 5	9°	0.38(5)	0.32	0.23	0.36	0.39	0.46	0.57	0.5
		12°	0.33	0.29	0.28	0.28	0.44	0.51	0.52	-
		15°	0.26	0.28	0.28(5)	0.34(	0.45	0.47	0.50	-
	Mark 4	9°	1	0.42	0.28	0.22	0.21	0.18	0.20	0.1
		12°	1	0.45	0.25	0.25	0.20	0.22	0.22	0.2
Decay distance/m	Mark 5	9°	4.66	6.33	7.10	7.72	7.31	5.14	4.94	6.4
		12°	5.1	6.33	6.59	6.95	5.35	3.86	4.01	-
		15°	6.49	7.77	6.90	6.02	4.74	4.89	4.94	-
	Mark 4	9°	-	4.53	6.38	7.26	6.38	7.59	7.10	6.8
		12°	-	4.53	5.87	6.48	7.00	6.95	7.10	9.0
Damped wavelength/m	Mark 5	9°	11.22	12.66	12.36	12.36	11.18	13.64	14.60	16.5
		12°	10.72	12.14	12.14	12.94	11.84	11.90	13.60	-
		15°	10.88	11.54	11.74	12.66	13.58	12.88	13.58	-
	Mark 4	9°		11.32	10.30	10.50	9.06	11.84	9.26	10.0
		12°		11.64	10.30	7.10	9.48	9.26	9.26	10.8
Natural wavelength/m	Mark 5	9°	10.82	12.00	12.02	11.52	12.14	12.12	11.12	13.5
		12°	10.08	12.62	11.66	12.44	11.84	11.96	11.52	-
		15°	8.46	11.08	11.24	11.88	12.12	11.38	11.74	-
	Mark 4	9°		10.28	9.88	10.24	8.86	11.64	9.08	9.9
		12°		10.40	9.96	6.78	9.48	8.76	9.08	10.8

Discussion

Anemometers

The Mark 4 was found to have a faster response than the Mark 5 at high wind speed, but at low wind speed there was only a small difference between them (see fig 6). This shows that, other than improving the threshold, the modifications made on the Met Office anemometer head have had negligible effect on its response time. This is supported by the fact that interchanging the heads did not significantly change the time constants of the Mark 4 or Mark 5 systems.

The slower response of the Mark 5 was due to smoothing in the transducer. The level of smoothing became increasingly significant with increasing wind speed and therefore increasing input signal frequency. The distance constant was found to increase for wind speeds greater than 50 knots (see fig 8). Above 60 knots the level of smoothing was sufficiently significant to prevent the system from being first order. This is shown in fig.7 by the non-linearity of the distance constant at the speeds.

Because the Porton is a much lighter anemometer than the Met Office one, it has a faster response (see fig.6) over the whole wind speed range investigated, especially at low speed.

The Porton system remained first order up to a wind speed of about 20 knots. Above this speed the transducer's smoothing became significant, similar to that of the Mark 5 at 50 knots. This is clearly shown by the gradual increase of the Porton's distance constant in fig.7. Despite this, at 80 knots the Porton still responds faster than the Mark 4.

The suitability of the method used for interpreting anemometer response data is demonstrated by the good agreement of the 95% response times found by two distinct calculations.

Using a "least-squares" regression, the equation of the Porton calibration curve (fig.15) was found to be:

$$V = 0.108(9)u - 0.149$$

where V = Porton output voltage (volts)

u = wind speed (knots)

Vanes

The results generally indicate that experimental errors are greater than any introduced by the possible non-linear response of the vane for large angles of attack.

The variation (scatter?) of results due to experimental error is generally large enough to hideany possible dependence of the results on the angle of attack. This supports the views of Wieranga (and Mazarella?) that the vane becomes dependent on angle of attack only for large angles (greater than 15° to 20°).

The results show that response of the vane, as used in the field, to a step change in direction, is affected by the small amount of friction in it up to speeds of 30 to 40 knots. For higher wind speeds the vane approaches a true second order system.

The Mark 4's larger divergence from a second order system at low wind speed, was due to the large amount of friction in the potentiometer.

The smoothing of the oscillating signal by the Mark 5 transducer was found to significantly attenuate the signal above speeds of 20 knots where the signal frequency became high.

In fig 9 the vane by itself tends to a damping ratio of h = 0.2 at high speed. As speed decreased, friction caused overshoot to be decreased, particularly when the magslip was replaced by a potentiometer. It can be seen that although the vane tended to oscillate most at high speed the oscillation was very significantly damped by the transducer before it was passed on to the pen-recorder. The damping of the transducer is probably useful. (The vane's damping ratio was found to be slightly angle dependent).

The vane settled more quickly in its new direction with respect to the air passing it, if its friction was high. This was shown by the dropping off of decay distance at low speed (fig.10). The transducer effectively reduced the required

length of air at high speed, i.e. the envelope enclosing the vane motion was reduced.

The fact that the decay distance was similar in magnitude to the anemometer's distance constant shows that the anemometer and vane are well matched.

The Mark 5 system had a constant natural wavelength due to the transducer's smoothing regularising the rate of oscillation of the system, with respect to the air passing it. This smoothing had the net effect of increasing natural wavelength from 9 m to 12 m (see fig.11). The Mark 4 gave a reasonably constant natural wavelength on the range 30-65 knots. It was however affected by friction at low speed and presumably spurious results were acquired for speeds over 65 knots.

Fig.12 shows that as the damping ratio of the Mark 5 system was increased, with wind speed so the damped wavelength was increased as predicted.

Wieranga proposed that damping ration, decay distance and natural wavelength are related to the vane's effective radius, r_v , torque parameter, a_v , fin area, S, and moment of inertia, J, by the following equations (all units in S.I.):

$$\text{Damping ratio, } h = 0.395 \left(\frac{a_v r_v^3 S}{J} \right)^{1/2} \qquad (4)$$

$$\text{Decay distance, } u.t_L = 7.37 \left(\frac{J}{a_v r_v^2 S} \right) \log \left(\frac{1}{L} \right) \qquad (5) \quad (L = \{1 - 0.63$$

$$\text{Natural wavelength, } u.t_n = 7.95 \left(\frac{J}{a_v r_v S} \right)^{\frac{1}{2}} \qquad (6)$$

The effective radius extends from the central axis to the aerodynamic centre of the fin, a quarter of the way across the fin from its leading edge.

These equations can be combined to form a series of curves (fig.14). It can be seen on this figure that the parameters of response motion for the vane at 50 knots, coincide very well. At this speed the vane is almost exactly described by a second-order system. This shows that Wieranga's response parameter inter-relationship equations work well for well-behaved vanes. The Mark 5 system's response parameters cannot be inter-related using these equations since the addition of the transudcer to the vane changes the system's record order nature.

By combining 4 with 5 and 6 to eliminate a_v two equations were derived for natural wavelength and decay distance in terms of known quantities. J was calculated to be 0.161 Kgm^2. The values of natural wavelength and decay distance were found to coincide with experimentally determined values for a wind speed of 50 knots.

It has, therefore, been shown that Wieranga's relationships work for the vane and will thus be useful for any theoretical approach to redesigning it.

Recorders

The time constants of the Mark 4 and Mark 5 pen recorders were found to be close to expected values. The expected recorder's modification of anemometer response to a step gust is shown in fig.4. Similarly the modification of vane response to a step change in direction is shown in fig.5.

It is hoped that these two figures give an indication of the relationship between the anemograph trace and the real fluctuations experienced by the sensors.

The UV-oscillograph trace is included to prove that its response could be regarded as instantaneous.

Conclusion

The response of the modified Met Office anemometer head, as used in the Mark 5 has not been improved, apart from a decrease in threshold.

The transducers of the Porton aemometer and the Mark 5 anemometer and vane systems show significant levels of smoothing at high speed, with a consequent attenuation of recorded signal.

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Mazarella D A (1972) "An inventory of specifications for wind measuring instruments", Bull.Amer.Meteor.Soc., 53, 860-871.

Gill G C (1959) "Meteorological Instrumentation" Professional lecture notes, CE 199, University of Michigan.

Atkinson "Feedback control for engineers"

Fig 1 , Anemometer response

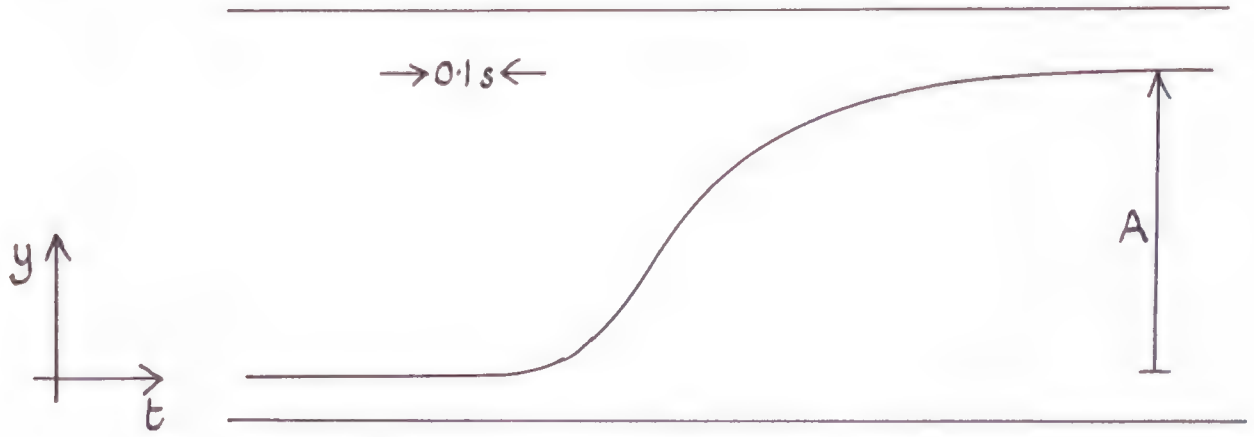


Fig 2 , Vane response

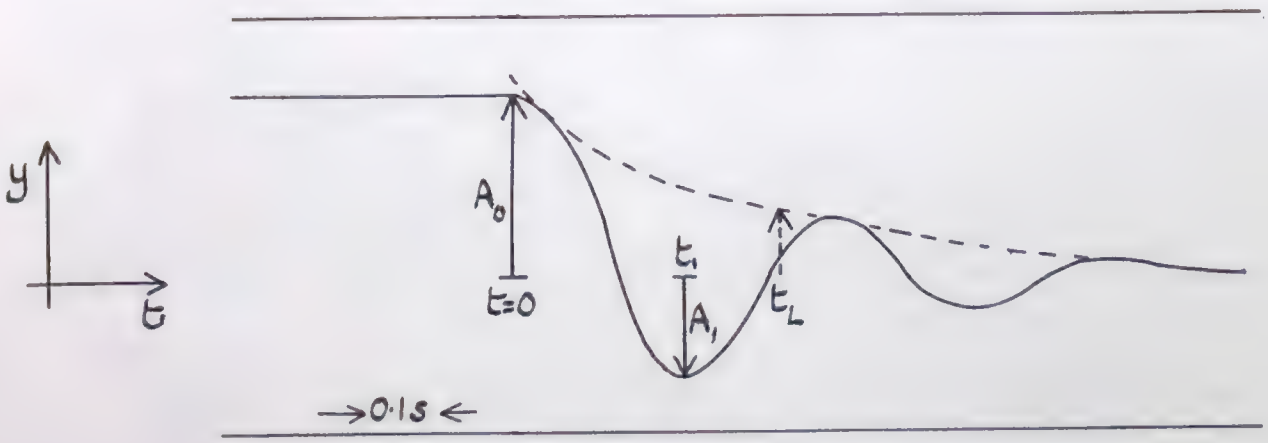


Fig 3a, Analysis system for the Mark 4 Anemometer

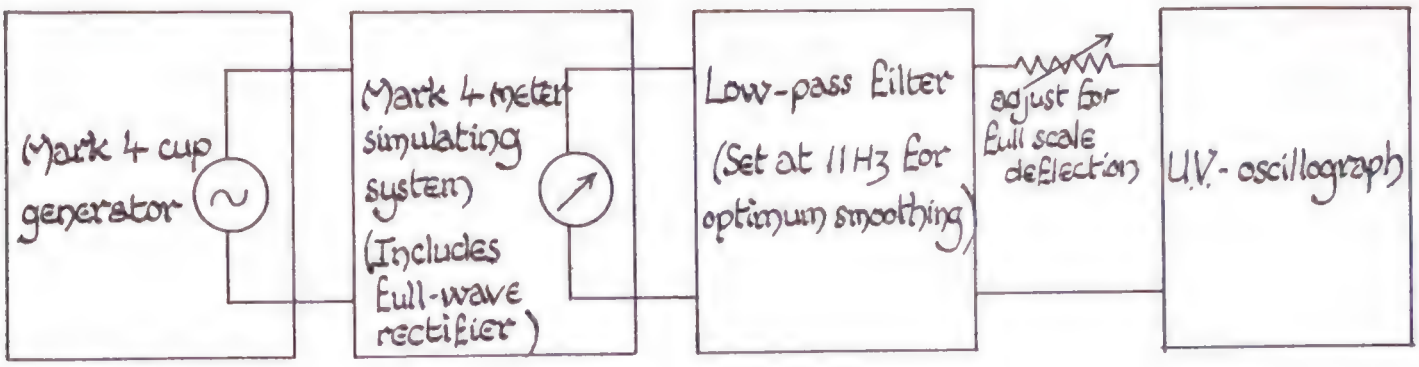


Fig 3b, Analysis system for the Mark 5 Anemometer.

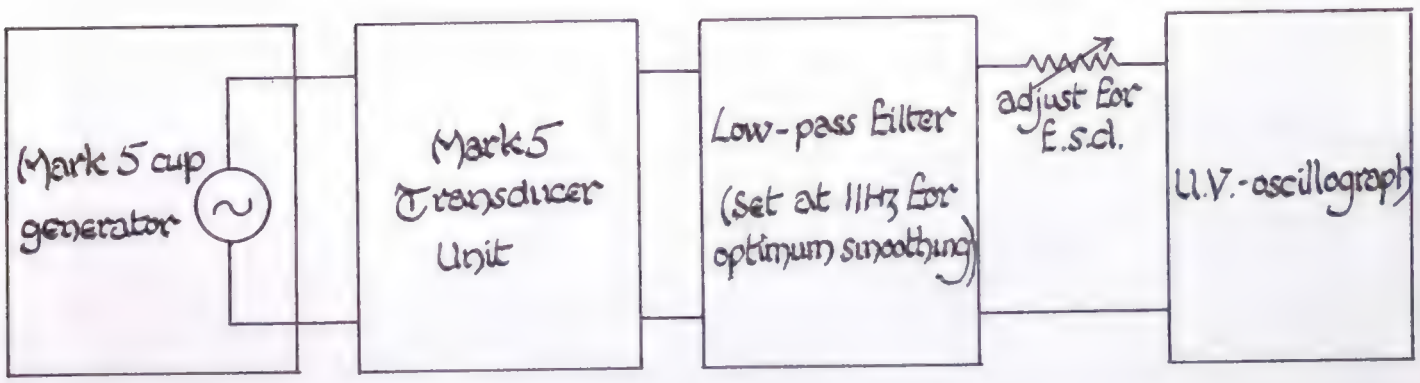


Fig 3c, Analysis system for vane

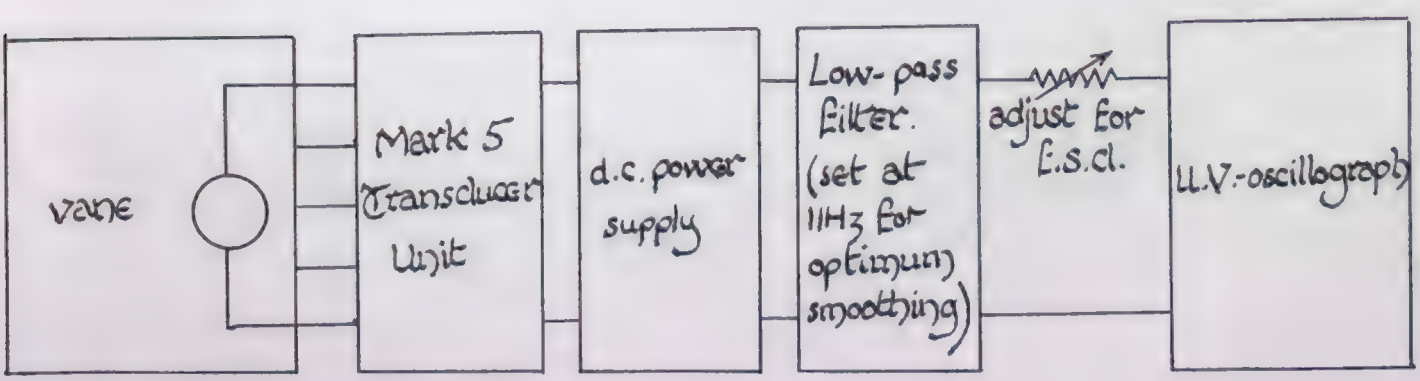


Figure 4

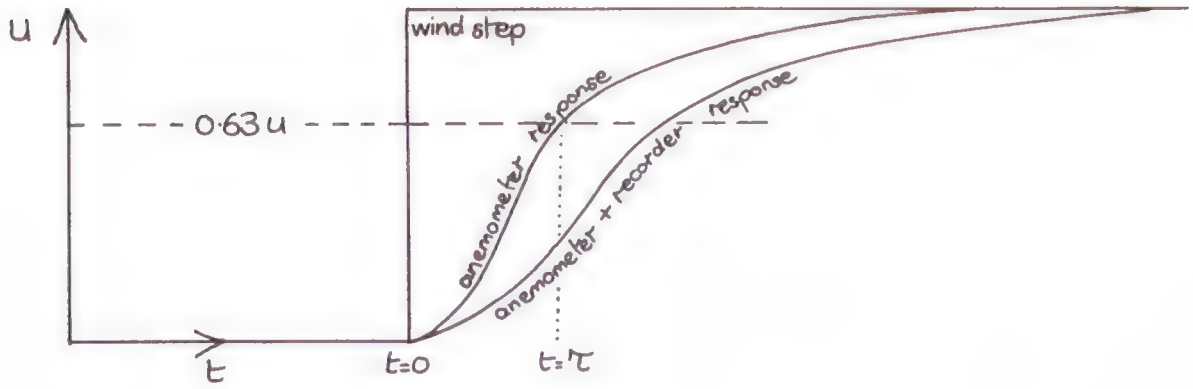


Figure 5

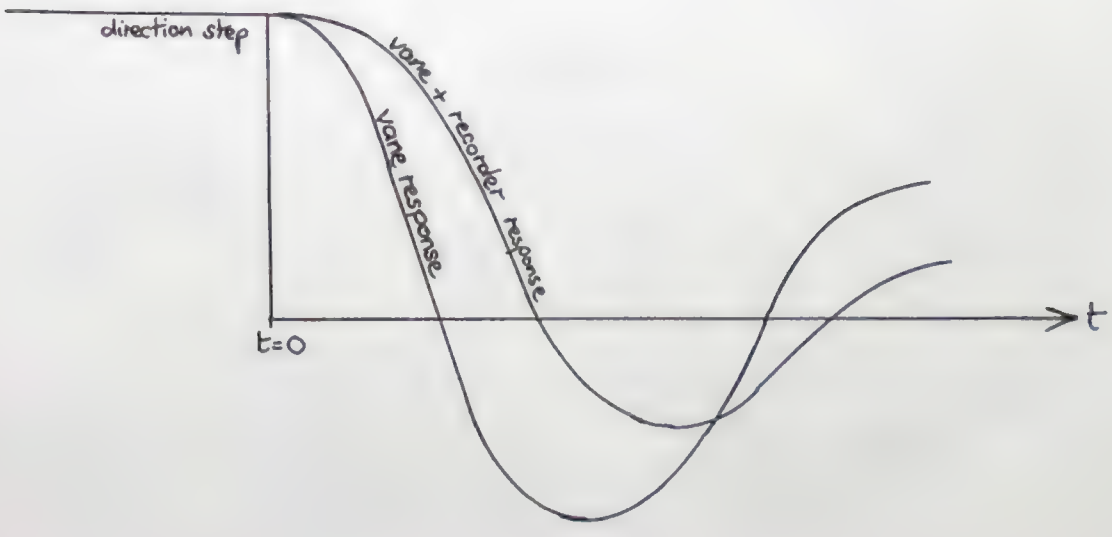


Fig 6, Variation of time constant with wind speed.

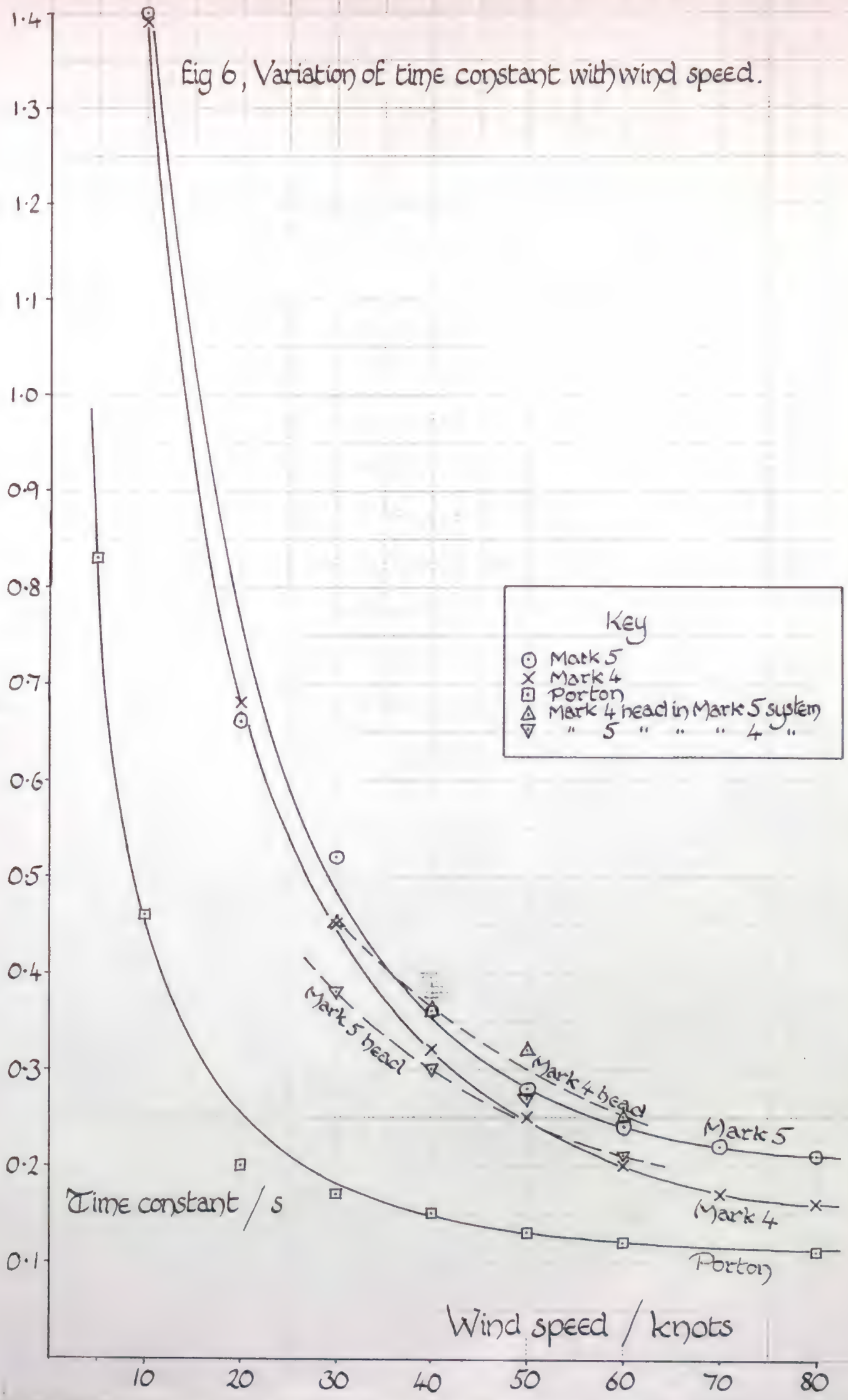


Fig 7, Variation of reciprocal time constant with wind speed. (Anemometers)

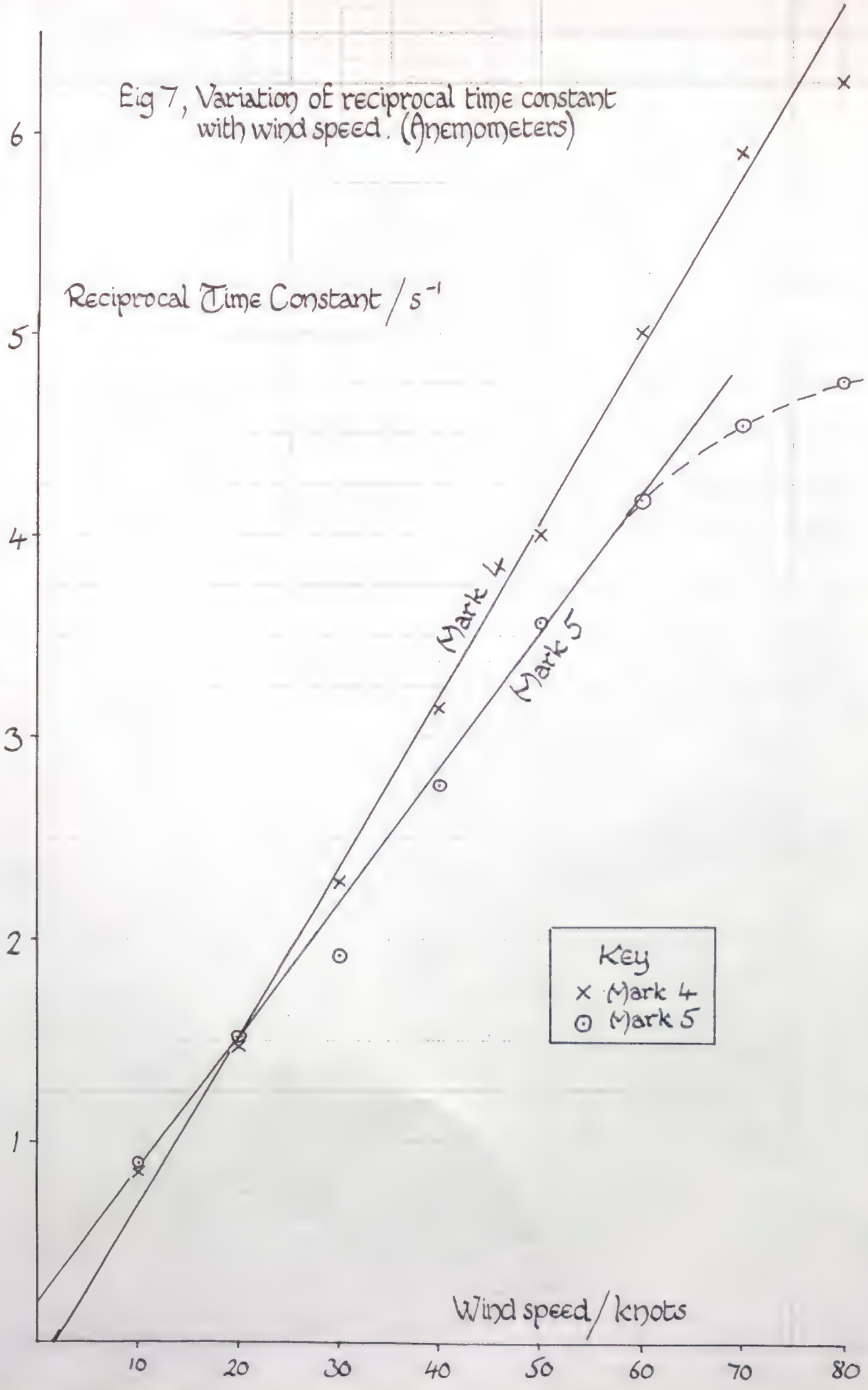


Fig. 8, Variation of instantaneous distance constant with wind speed. (Anemometers)

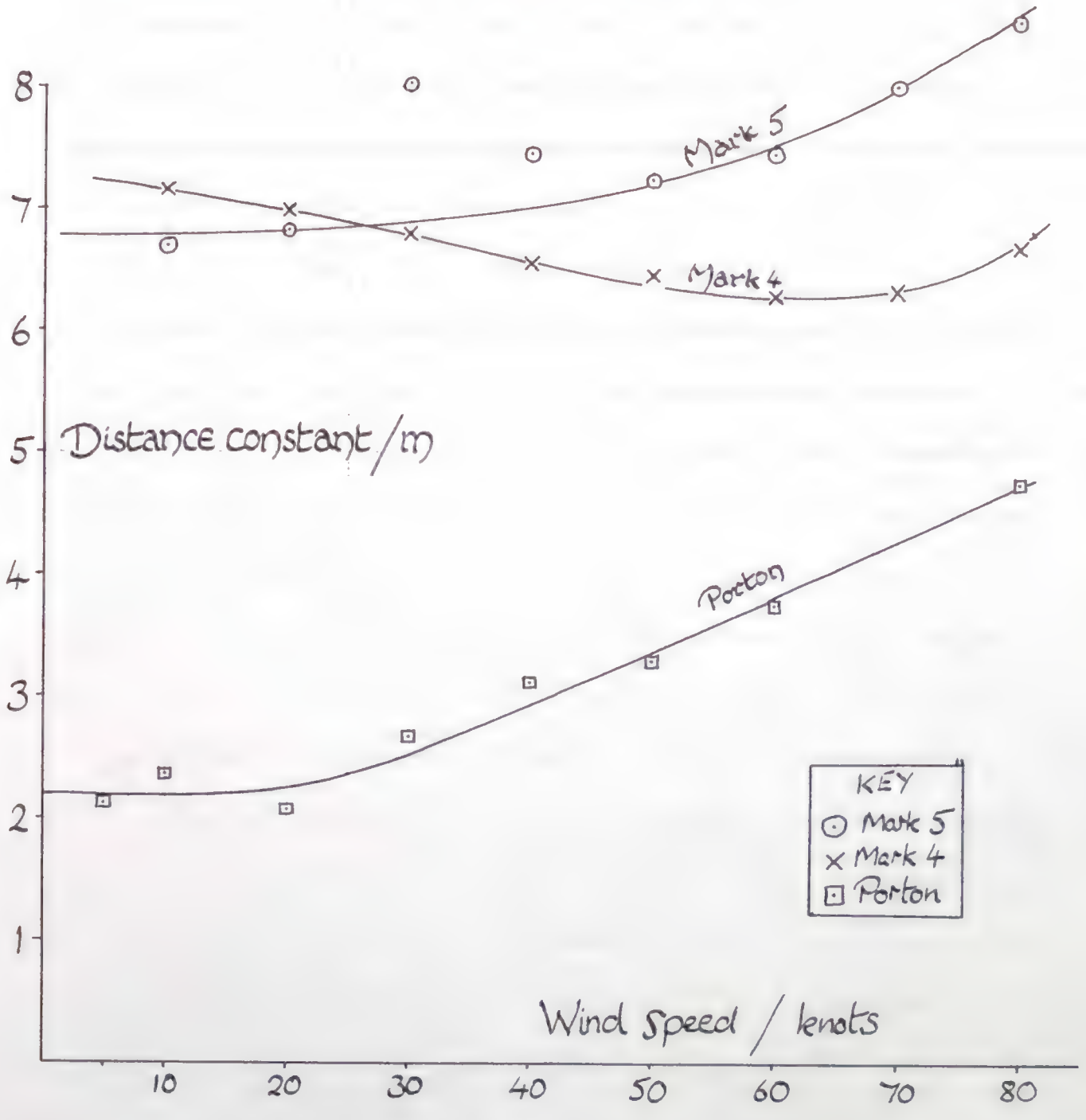


Fig 9, Variation of damping ratio with wind speed.

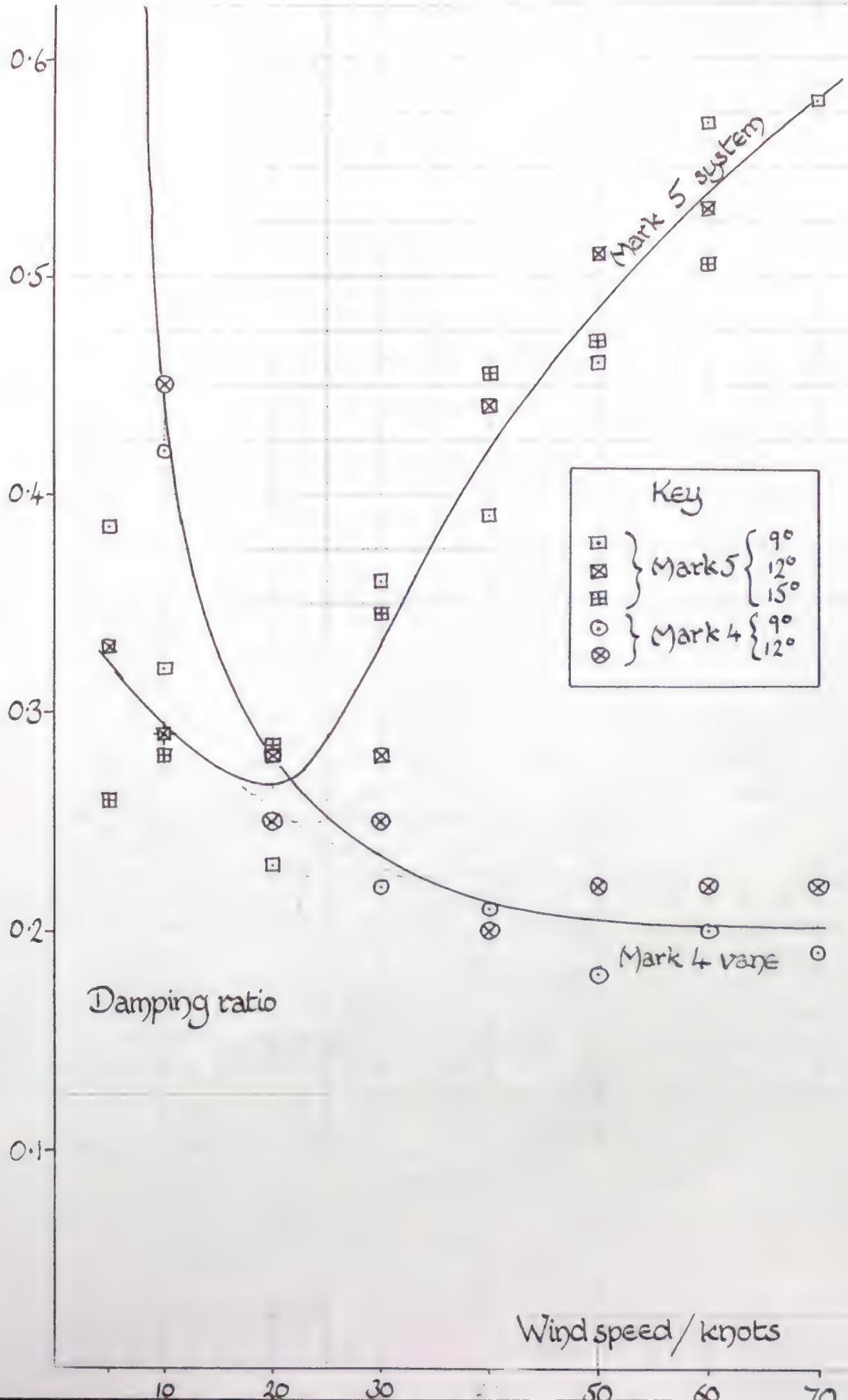


Fig 9, Variation of damping ratio with wind speed.

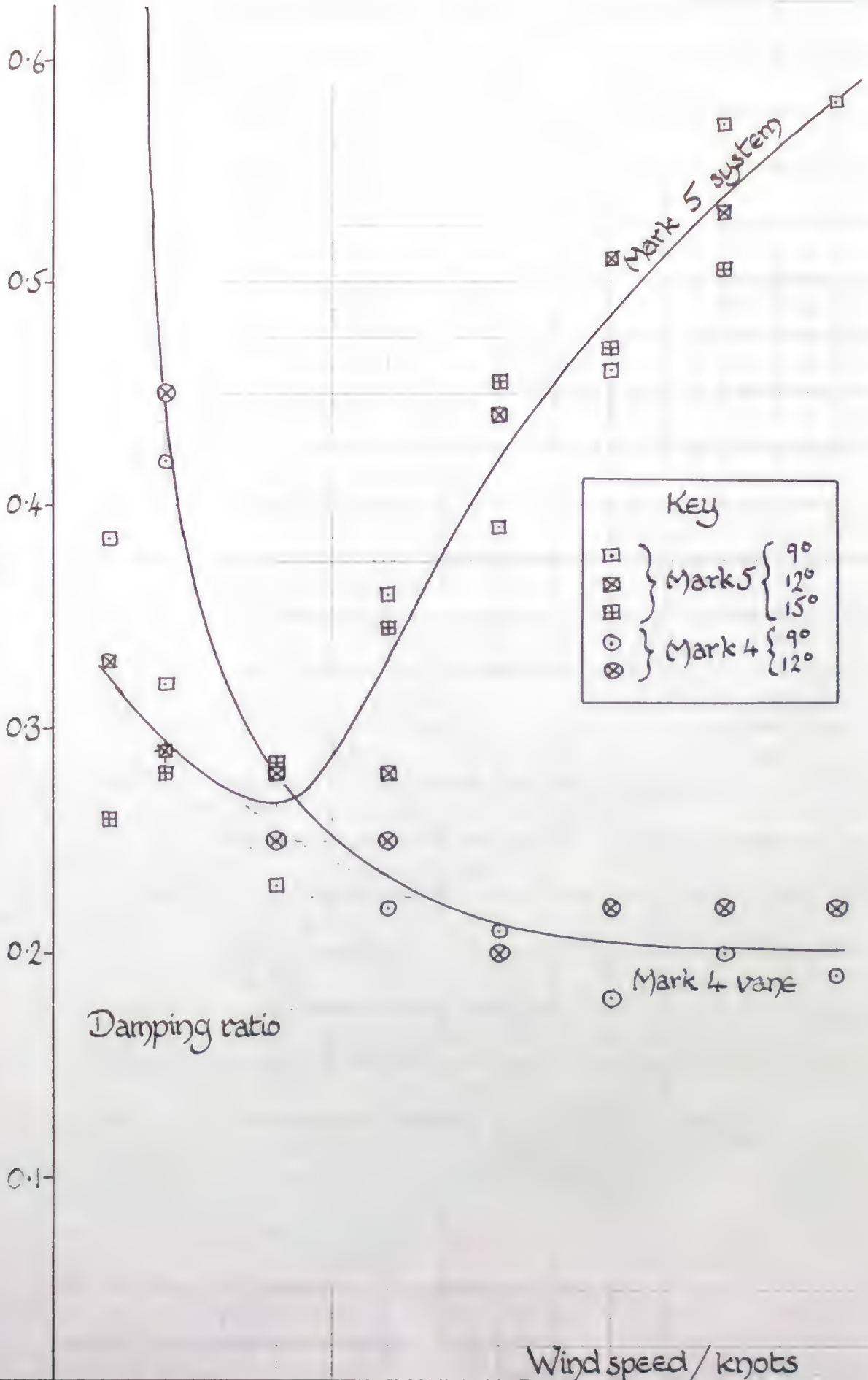


Fig 10, Variation of decay distance with wind speed.

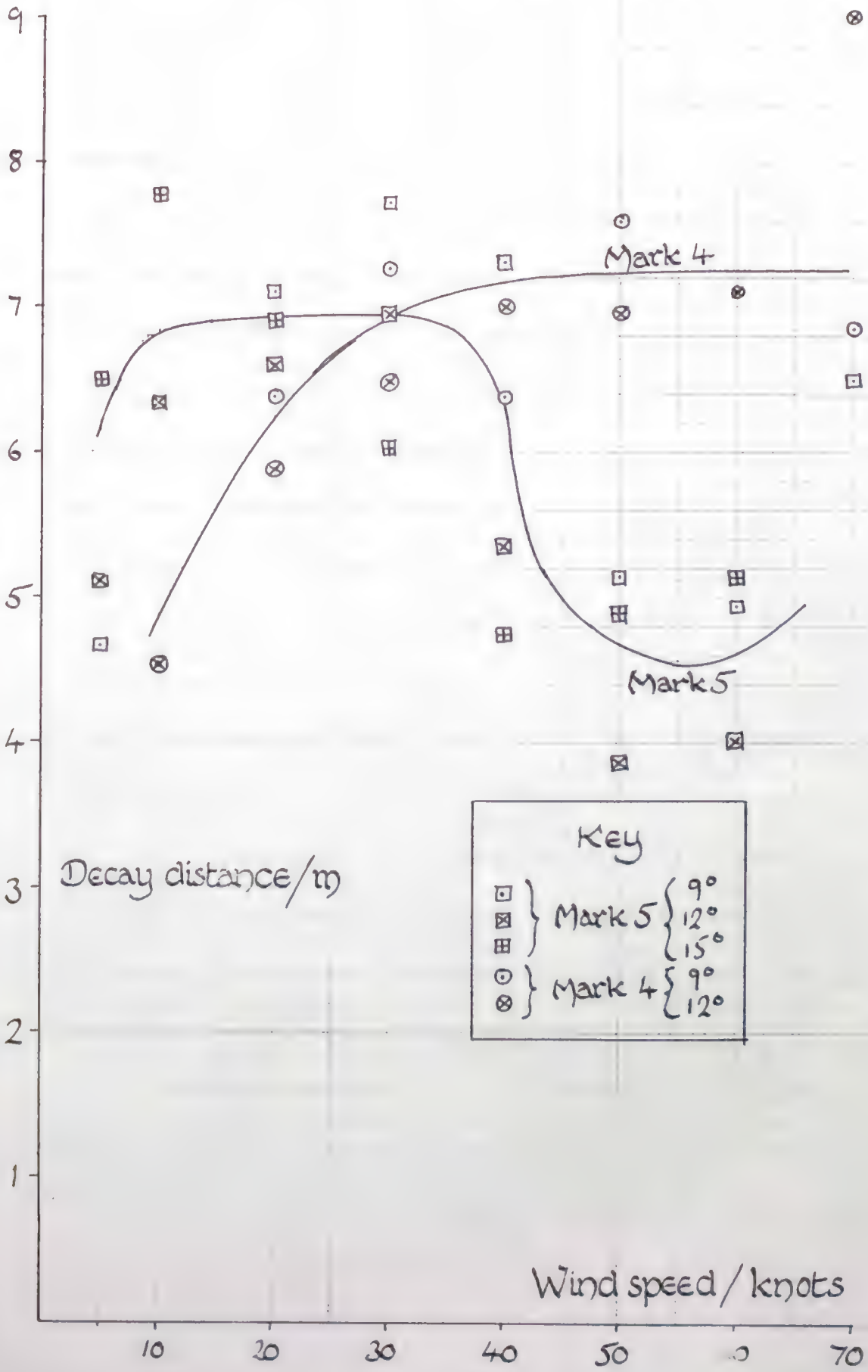
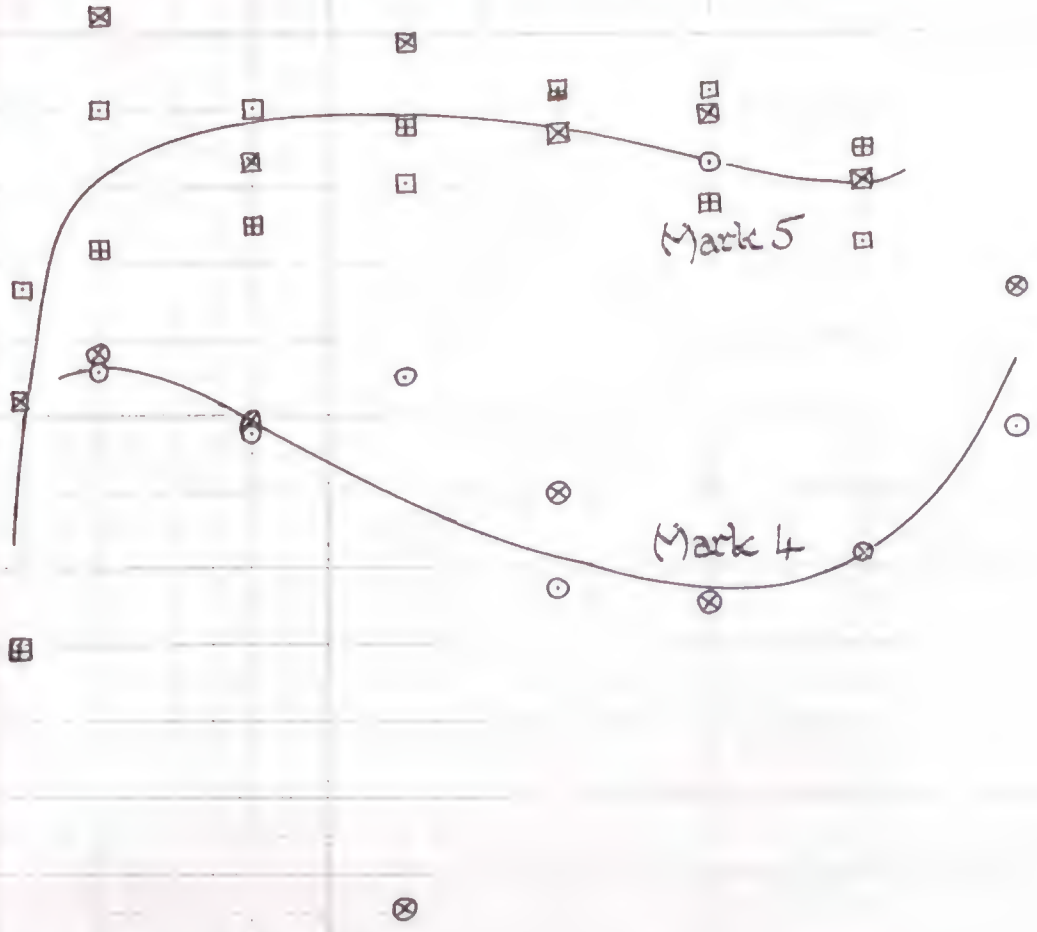


Fig 11, Variation of natural wavelength with wind speed.



Natural wavelength / m

Key

Mark 5: 9°, 12°, 15°

Mark 4: 9°, 12°

Wind speed / knots

10 20 30 40 50 60 70

Fig 12, Variation of damped wavelength with wind speed.

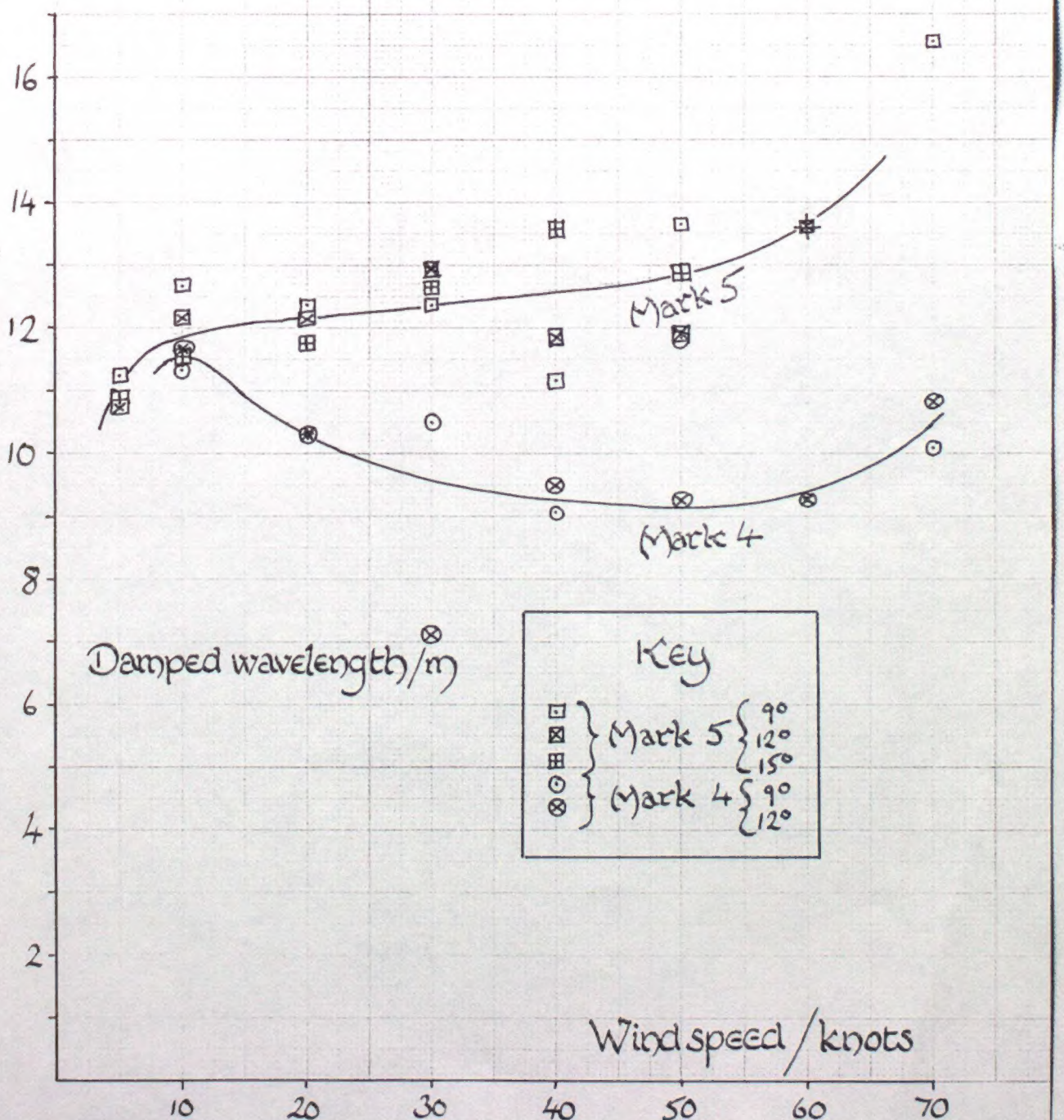
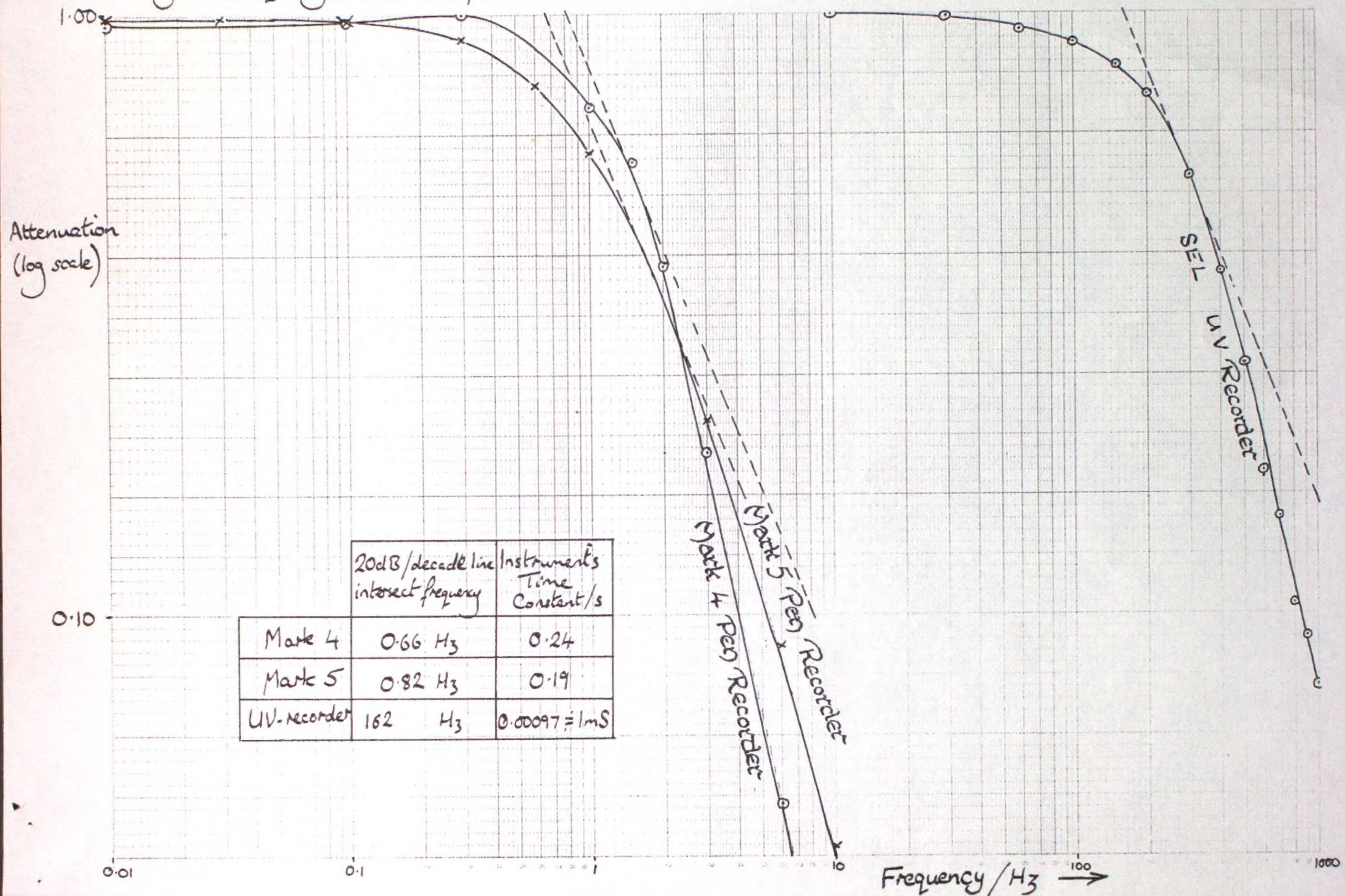


Fig 13 Frequency Response of Mark 4 and Mark 5 pen recorders, and UV Recorder



	20dB/decade line intersect frequency	Instrument's Time Constant/s
Mark 4	0·66 Hz	0·24
Mark 5	0·82 Hz	0·19
UV-recorder	162 Hz	0·00097 ≒ 1mS

Fig 14, Inter-relationship of response parameters for Mark 4 vane.

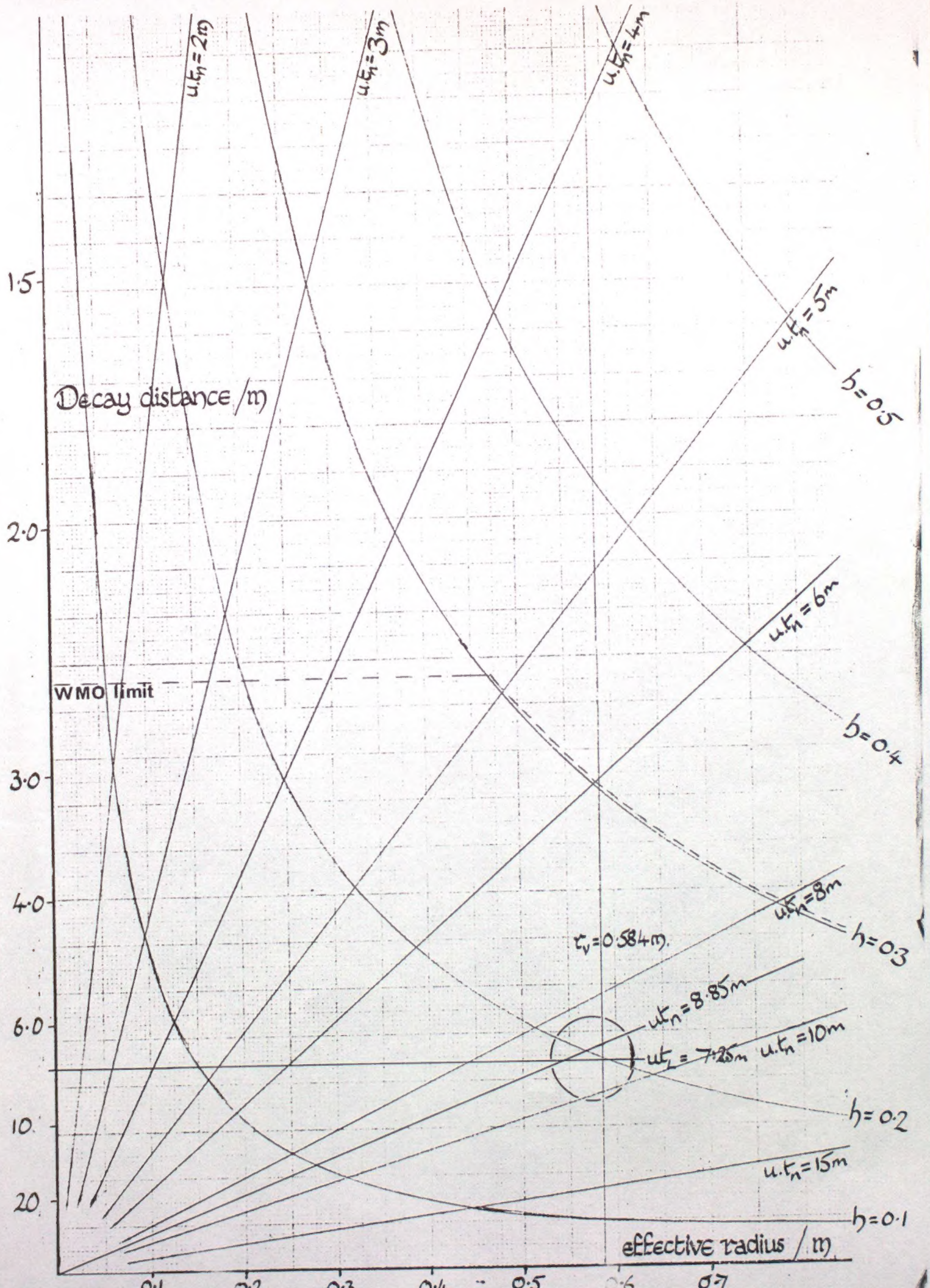
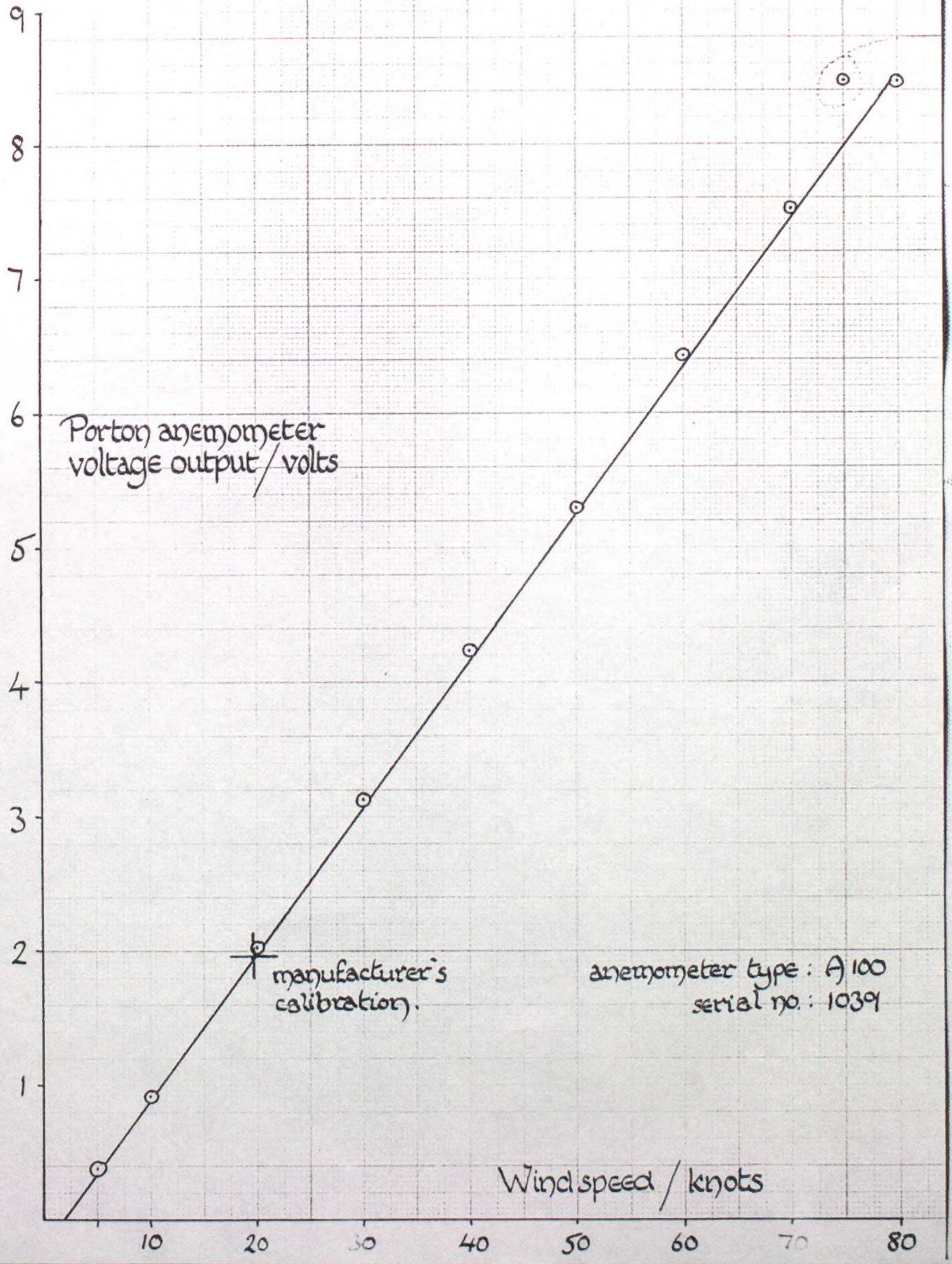



Fig 15, Calibration of Porton anemometer.